Physics-based Parameterizations of Air-sea Fluxes at High Winds

Tetsu Hara
Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882
phone: (401) 874-6509 fax: (401) 874-6728 email: thara@uri.edu

Stephen E. Belcher
Department of Meteorology, University of Reading, Reading, RG6 6BB, UK
phone: (44) 118-931-6646 fax: (44) 118-931-8905 email: s.e.belcher@reading.ac.uk

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LONG-TERM GOALS

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

OBJECTIVES

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. But the role of these breaking waves on air-sea fluxes is at present almost completely unknown. In this project we develop recent understanding of surface wave processes, and in particular breaking waves and their statistics, to develop a framework for accounting for wave breaking in air-sea fluxes in high winds. The specific objectives are:

- To develop a theoretical model for the statistics of breaking wave coverage, based on the dynamics of the surface waves.
- To use these statistics to formulate a methodology for accounting for the exchange of momentum and kinetic energy between the atmosphere and ocean that results from the breaking waves.
- To integrate this methodology into the framework developed by Makin and co-workers (Makin et al. 1995, Makin and Kudryavtsev 1999) for air-sea exchange for non-breaking waves.
- To then develop a model for transfer of scalars, such as heat and moisture, that accounts for both breaking and non-breaking waves.
- To validate, where possible, the components of these models against observational data.
- To clarify limitations of bulk parameterizations and identify improvements.

APPROACH

The approach is:

- To validate our recent model results of the equilibrium range of surface wave spectra and breaking wave statistics (Hara and Belcher 2002).

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- To develop a model of momentum flux (wave-induced stress and turbulent stress), mean wind profile, and TKE budget in the atmospheric surface layer at high sea states including the contributions from breaking waves.
- To model effects of breaking waves on transfer of scalars, such as heat and moisture, in the wave boundary layer.
- To model the effects of waves on the Ekman layer in the ocean, with a view to modeling the vertical profiles of the mean current, TKE, and TKE flux across the wave boundary layer.
- To develop new flux parameterizations in the atmosphere. An important question to be addressed here is how the presence of breaking waves affects the air-sea fluxes in realistic oceanic conditions. Where possible the new parameterizations will be compared with observations conducted under CBLAST.

WORK COMPLETED

We have developed a new model of momentum flux, mean wind profile, and TKE budget in the atmospheric wave boundary layer. The model is based on the conservation of energy and momentum within the wave boundary layer. At the top of the wave boundary layer there is a downward energy flux, which is balanced by the dissipation of the turbulent kinetic energy due to viscosity, and the flux of energy into surface waves. The former determined by the local, reduced turbulent stress at each height. The latter is obtained by integrating the flux into each surface wave spectral component, making use of the equilibrium spectral form obtained by Hara and Belcher (2002). This approach yields an analytical expression for the wind profile, the equivalent surface roughness, and Charnock's constant over mature seas.

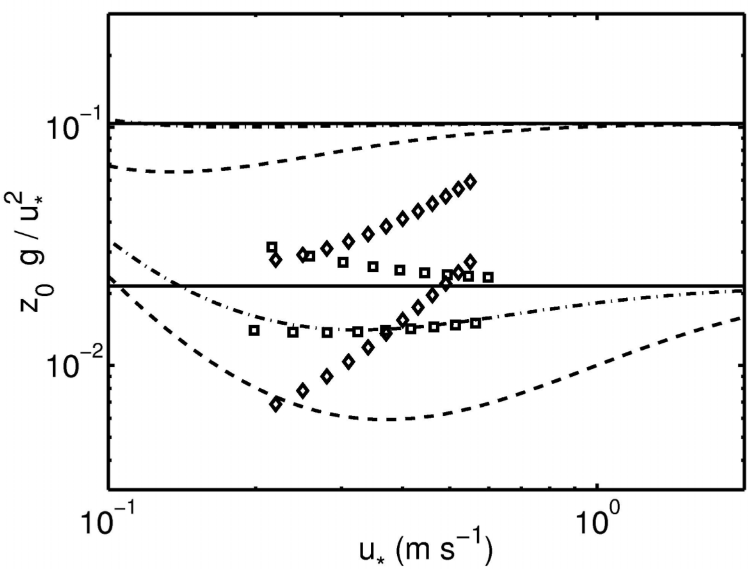

Figure 1: Upper and lower bounds of the Charnock coefficient versus friction velocity for mature seas based on our wave boundary layer model. Lines are results calculated with the cutoff (upper bound) wavenumber of 100 rad m^{-1} (dashed lines), 400 rad m^{-1} (dash-dot lines), and infinity (solid lines). Diamonds are results calculated based on the ratio of the total stress and viscous stress estimated by Banner and Peirson (1998), which agree well with the squares that are empirical estimates by Banner and Peirson (1998).

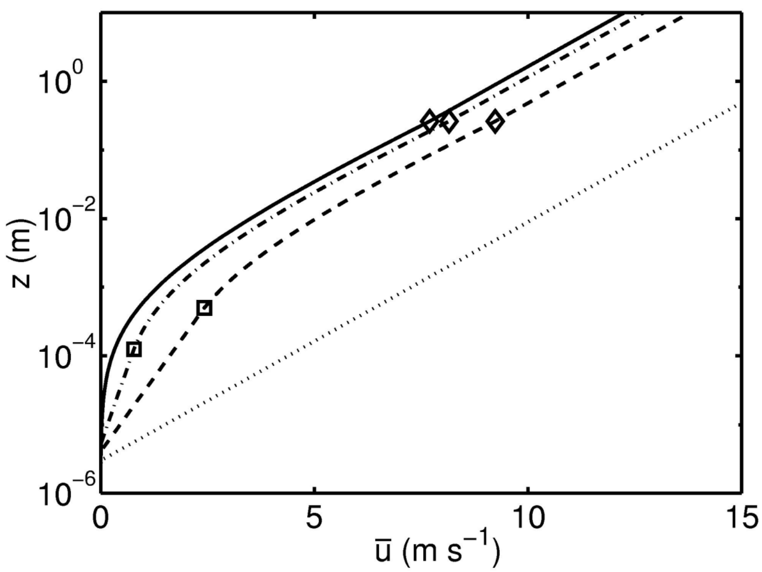

Figure 2: Mean wind profiles over mature seas based on our wave boundary layer model. Friction velocity is 0.5 m s^{-1}. Lines are results calculated with the cutoff (upper bound) wavenumber of 100 rad m^{-1} (dashed lines), 400 rad m^{-1} (dash-dot lines), and infinity (solid lines). Diamonds and squares indicate top and bottom of the wave boundary layer, respectively. Dotted line shows wind profile over a smooth solid surface.

A manuscript based on the results is currently under review (submitted to Journal of Physical Oceanography in March, 2003 and resubmitted after revision in July, 2003).

We have also estimated the drag coefficient and the Charnock coefficient over developing and complex seas by combining ocean wave models and a wave boundary layer model. The combined model estimates the wind stress by explicitly calculating the wave-induced stress. In the frequency range near the spectral peak, WAVEWATCH-III is used to estimate the spectra, and the spectra in the equilibrium range are determined by the analytical model by Hara and Belcher (2002). This approach allows us to estimate the drag coefficient and the equivalent surface roughness for any surface wave fields. Numerical experiments have been performed for constant winds from 5 m/s to 45 m/s to investigate the effect of mature and growing seas on air-sea momentum exchange. For mature seas, the Charnock coefficient is estimated to be about 0.01 ~ 0.02 and the drag coefficient increases as wind speed increases, which are within the range of previous observational data. With growing seas, our results for winds less than 30 m/s show that the drag coefficient is larger with younger seas, being consistent with earlier studies. For winds higher than 30 m/s, however, our results show a different trend, that is, very younger waves yield less drag (Figure 3). This is because the wave-induced stress due to very young waves makes a small contribution to the total wind stress in very high wind conditions.

A manuscript based on the results is currently under review (submitted to Journal of Atmospheric Sciences in August, 2003).

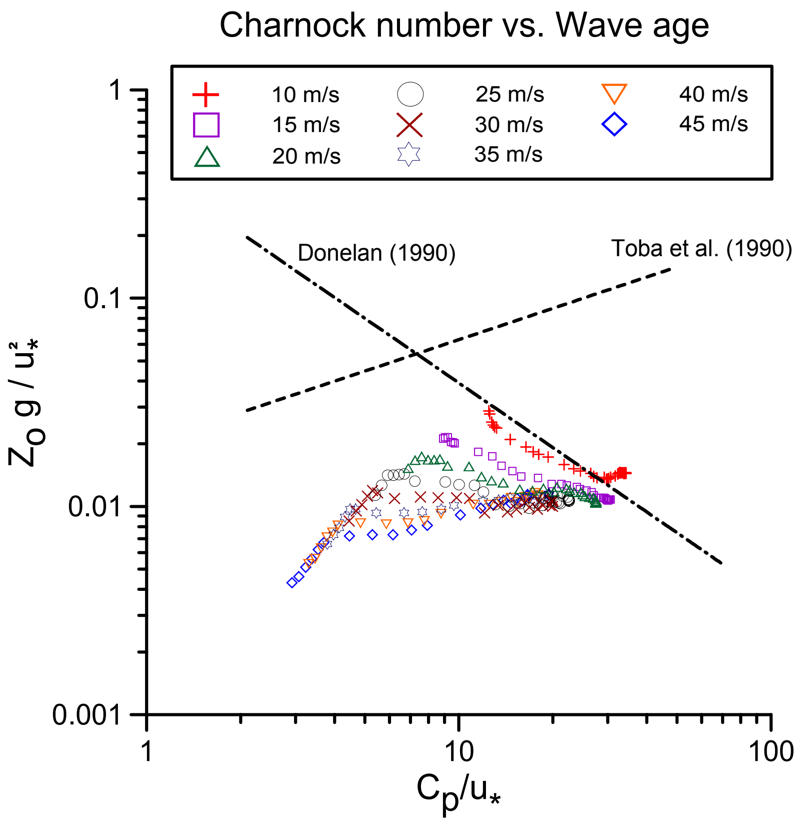

Figure 3: Nondimensional roughness length (Charnock coefficient) versus wave age, which are estimated from the present model for constant winds from 10 m/s to 45 m/s. Dashed line and dash dot line are empirical estimates by Toba et al. (1990) and Donelan (1990), respectively.

We have also made progress in modeling the effects of surface waves on near-surface Ekman layer currents in the water. The Stokes drift associated with the surface waves deforms vorticity in the Ekman layer. This vorticity has two sources: planetary vorticity, and turbulent vorticity. We have developed models for both processes.

Firstly, the deformation of the planetary vorticity by the wave-induced Stokes drift leads to a new force, the Coriolis-Stokes force, which acts in the upper layers of the wind-driven mixed layer. The Coriolis-Stokes force changes the whole mean flow within the Ekman layer. We have developed a quantitative analytical model and performed large eddy simulations of this process. Figure 4 shows a hodograph of the Ekman current calculated with the model both including the effects of Stokes drift on the planetary vorticity, and calculated ignoring this process. Also shown are measurements from the Lotus data (Price & Sundermeyer 1999). Clearly the inclusion of the Stokes drift effect on the planetary vorticity yields very significantly better agreement with the measurements than is obtained when this process is neglected. Comparisons of the model with two other sets of measurements show similar agreement (see Lewis & Belcher 2002). These findings suggest that large-scale ocean models should represent the Coriolis-Stokes force. We have shown how this can be done by modifying the boundary condition at the air-sea interface. This work has led now to two journal articles that are under review, namely Lewis & Belcher (submitted to Dyn. Atmos. & Ocean. in December 2002 and now revised and resubmitted) and Polton, Lewis & Belcher (Submitted to J. Phys. Oceanogr. July 2002).

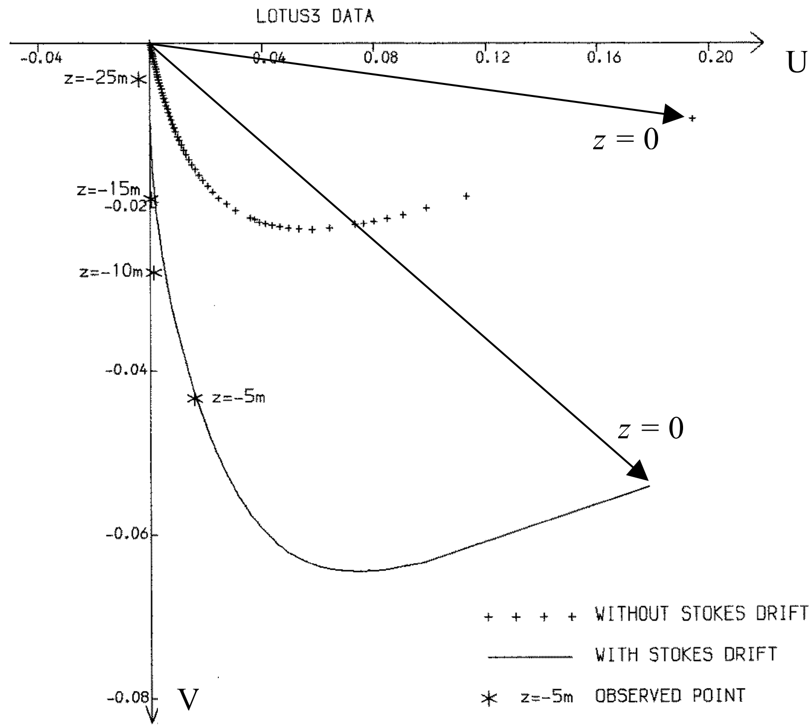

Figure 4. Hodograph of the current profile in the Ekman layer. Solid curve: theoretical solution obtained including the deformation of planetary vorticity by Stokes drift; pluses: conventional theoretical solution obtained by ignoring the effects of Stokes drift; stars: measurements from LOTUS3.

Secondly, we have developed a model for the effects of Stokes drift on the turbulent vorticity in the Ekman layer. This process leads to the development of Langmuir circulations on a whole range of length scales. We have developed a linear analytical model for the deformation of the turbulent vorticity by the Stokes drift. The results of this model compare well with the turbulent statistics computed for Langmuir turbulence by McWilliams et al (1997) (see Teixeira & Belcher 2002). The significance of this result is that it shows how any vorticity in the Ekman layer can produce vortices aligned in the wind direction, yielding structures that resemble Langmuir circulations.

RESULTS

In the absence of breaking waves, the mean wind profile inside the wave boundary layer is uniquely determined from the conservation of energy and momentum. The drag coefficient and the equilvalent surface roughness are mainly determined by the (effective) wave age and the sheltering wave age. The former quantity determines the width (in wavenumber) of the equilibrium range, while the latter determines the level of the equilibrium wave spectrum. The drag coefficient also depends on the shape of the spectrum of gravity-capillary waves at lower wind speeds. With growing seas, the drag coefficient is larger with younger seas for winds less than 30 m/s. For winds higher than 30 m/s, however, very younger waves yield less drag. The Charnock coefficient is constant (independent of wind stress) when: (1) The effects of viscosity and surface tension on waves are negligible; and (2) The wave spectrum is fully developed and (3) The sheltering wavenumber is independent of wind stress.

The deformation of the planetary vorticity by Stokes drift associated with surface waves is an important process that shapes the mean currents through the depth of the mixed layer. Including this process yields a model for currents in the Ekman layer that agree well with measurements. We recommend that large-scale models of ocean circulation include this process. We have shown how this can be done efficiently by modifying the boundary condition at the air sea interface. Any vorticity in the Ekman layer is also deformed by the Stokes drift of the waves and is stretched to produce streamwise vortices that resemble Langmuir vortices.

IMPACT/APPLICATIONS

This program of work promises a one dimensional (1d) model of the atmospheric and oceanic boundary layers in the vicinity of the air--sea interface that accounts for both breaking and non-breaking waves. The model will, given the ten meter wind speed, temperature and humidity and surface wave parameters, produce wave breaking statistics, wind and current profiles, fluxes and flux profiles and the turbulent kinetic energy budgets through the 1d air and water wave boundary layers. These results may be used as a basis for any future modeling efforts of ocean-atmosphere interaction processes.

TRANSITIONS

The results from this project are used to develop a new set of physics-based parameterizations of air-sea fluxes, which are valid for the whole range of wind speeds and can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems.

RELATED PROJECTS

TH has an ongoing NSF project (2000-2004) to address the air-sea momentum flux at high sea. This NSF project is a subset (atmospheric wave boundary layer only) of this ONR project and therefore these two projects will be fully integrated. TH's main contribution to this ONR project will be in Year 4 and 5 (2004-2005).

New knowledge gained from our study has been incorporated in coupled atmosphere-wave-ocean numerical models under another NSF project (2000-2004) by TH and his colleagues. Current numerical wave models are not capable of predicting accurately short wind waves at frequencies much higher than the spectral peak. Instead they patch a parameterized form of spectra. More accurate information about short wind wave spectra and their breaking statistics resulting from this study will improve the accuracy of the numerical wave prediction and will thus enhance the performance of coupled numerical models.

SEB has an ongoing project funded by the Leverhulme Trust (a UK charity that funds fundamental scientific research) into the dynamics of Langmuir turbulence in the ocean mixed layer. The aim is to develop understanding of the dynamical processes that determine the lifecycle of streamwise vortices in the ocean mixed layer. The model will account for the turbulence injected into the water column from breaking waves. Hence this Langmuir turbulence project will benefit from the parameterization of the oceanic wave boundary layer developed in the work proposed here.

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